

Light scalars coupled to photons and non-newtonian forces

Arnaud Dupays

INAF-IASF, Via E. Bassini 15, I-20133 Milano, Italy

Eduard Massó and Javier Redondo

*Grup de Física Teòrica and Institut de Física d'Altes Energies,
Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain*

Carlo Rizzo

*Laboratoire Collision Agrégats et Réactivité, IRSAMC,
Université Paul Sabatier et CNRS, 31062 Toulouse, France*

(Dated: Preprint UAB-FT-618)

A particle ϕ coupling to two photons couples also radiatively to charged particles, like protons. If the particle is a light scalar this induced coupling leads to spin-independent non-newtonian forces. We show that the experimental constraints on exotic, fifth-type forces lead to stringent constraints on the $\phi\gamma\gamma$ coupling. We discuss the impact on the recent PVLAS results and the role of paraphoton models introduced to solve the PVLAS-CAST puzzle.

PACS numbers:

Keywords:

Spinless light particles are a common prediction of many theories that go beyond the standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge theory. Probably the most famous of them is the axion [1], an unavoidable consequence of the introduction of a new global $U(1)$ symmetry designed to solve the QCD CP-problem [2]. There are other examples of light particles; some are pseudoscalar like the axion itself and some are scalar particles. We call them axionlike particles (ALPs).

In general, a spinless particle couples to two photons, and of course in principle it has also couplings to matter. But the $\gamma\gamma$ coupling is particularly interesting because many experimental searches for ALPs are based on it. One of these searches is based on the so-called haloscope [3], where axions or some other similar particles forming part of the dark matter in the galactic halo can convert into photons in a cavity with a strong magnetic field. Another search is to look for ALPs produced in the Sun converting into photons in a detector having a strong magnetic field; this is called helioscope [3]. Still another experiment searching for ALPs and that uses the $\gamma\gamma$ coupling looks for optical dichroism and birefringency in a laser that propagates in a magnetic field [4].

While the most recent haloscope [5] and helioscope [6] experiments have not found any signal and thus have put limits on model parameters, the third type of experiment described above has reported a positive signal. Indeed, the PVLAS collaboration finds a rotation of the polarization plane of the laser as well as an induced ellipticity [7]. There is an exciting interpretation of these results in terms of a new scalar particle ϕ , that should have a mass $m_\phi \sim 10^{-3}$ eV and a $\phi\gamma\gamma$ coupling scale of about $M \sim 10^5$ GeV -see equation (1) below for the definition of M .

The purpose of this paper is to show that in the case that the particle ϕ is indeed a light **scalar**, the $\phi\gamma\gamma$ coupling leads to the existence of long-range spin-independent non-newtonian forces. Our calculation will allow us to find a very stringent limit on the coupling, using the experimental null results coming from searches for new forces.

A scalar particle couples to two photons with the lagrangian

$$\mathcal{L}_1 = \frac{1}{4M} \phi F^{\mu\nu} F_{\mu\nu} \quad (1)$$

The key point is that (1) induces radiatively a coupling to charged particles, for example to protons (see Fig 1). The induced coupling will have the form

$$\mathcal{L}_2 = y \phi \bar{\Psi} \Psi \quad (2)$$

where Ψ is the proton field and y the Yukawa coupling. The loop diagram is logarithmically divergent.

In order to treat physically this divergence, we notice that (1) corresponds to a non-renormalizable term in the lagrangian and as such is expected to be valid only up to a high-energy scale Λ , where new physics has to appear. We integrate momenta in the loop of Fig.1 only until Λ , so that we cut the divergence with the scale Λ .

The logarithmically divergent part of the diagram of Fig.1 is well-defined and is the leading radiative contribution to y . Approximating y by this term we obtain

$$y = \frac{3}{2} \frac{\alpha}{\pi} \frac{m_p}{M} \log \frac{\Lambda}{m_p} \quad (3)$$

In principle there is also a tree level Yukawa term (2) in the theory, and there could be some cancelation between the tree level and the radiatively induced coupling (3).

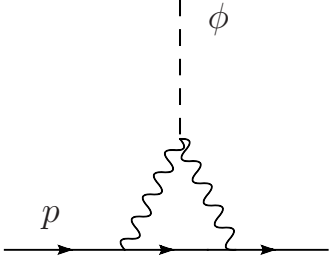


FIG. 1: Loop diagram.

We regard this possibility as very unnatural, and will use (3) for our estimates.

The Yukawa coupling (2) leads to non-newtonian forces between two test masses m_1 and m_2 , due to ϕ exchange. The total potential between 1 and 2 is

$$V(r) = G \frac{m_1 m_2}{r} + \frac{y^2}{4\pi} \frac{n_1 n_2}{r} e^{-m_\phi r} \quad (4)$$

Here n_i is the total number of protons in the test body i . In (4) we have neglected the new electron-proton and electron-electron force since the corresponding value for y in the case of the electron is smaller than (3) by a factor m_e/m_p . When the two test bodies are constituted each by only one element, with atomic numbers Z_1 and Z_2 , and mass numbers A_1 and A_2 , we can approximate (4) by

$$V(r) \simeq G \frac{m_1 m_2}{r} \left[1 + \frac{1}{G m_p^2} \frac{y^2}{4\pi} \left(\frac{Z}{A} \right)_1 \left(\frac{Z}{A} \right)_2 e^{-m_\phi r} \right] \quad (5)$$

where now in the second term inside the square brackets i.e., the term containing the correction to the newtonian potential, we have approximated $m_i \simeq A_i m_p$.

The non-newtonian part of the potential we have obtained has two clear properties: it has a finite range m_ϕ^{-1} and depends on the composition of the bodies, i.e. on their Z/A values. We can use the abundant experimental bounds on fifth-type forces to limit our parameter M as a function of m_ϕ .

To see how we proceed we find now the limit in the interesting ranges $m_\phi^{-1} \sim (\text{meV})^{-1} \sim 0.2 \text{ mm}$, with the PVLAS results in mind. Bounds on new forces have been obtained by experiments designed to measure very small forces. In the submillimeter range, in 1997 authors of ref. [8] using a micromechanical resonator designed to measure Casimir force between parallel plates gave limits on new forces, and they also estimated the corresponding limits on the mass and inverse coupling constant of scalar particles. Also, strong experimental limits on new forces have been published in [9], where they use a torsion pendulum and a rotating attractor in the framework of tests of the gravitational inverse-square law. The most strict bounds have been obtained very recently by using torsion-balance experiments [10].

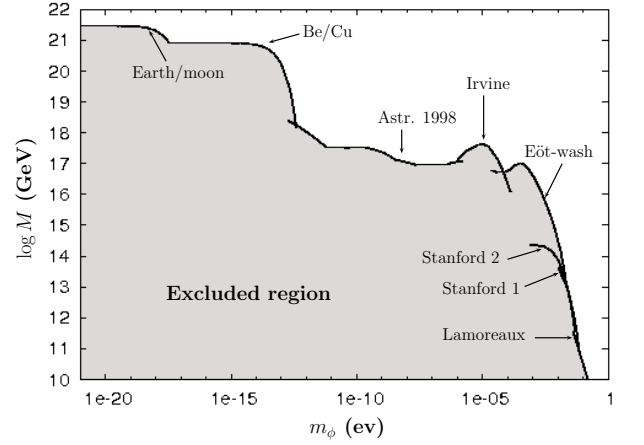


FIG. 2: Constraints in the $\log M - m_\phi$ plane. Lines labeled Earth/moon and Astr. 1998 show constraints from astrophysical observations, Refs. [11] and [12] respectively. Lines labeled Be/Cu, Irvine, Eöt-wash, Stanford 2, Stanford 2, and Lamoreaux show experimental constraints, Refs. [13], [14], [10], [15], [16], and [17] respectively. The shaded region is excluded.

The limit from the experiment presented in ref. [10] for $m_\phi = 10^{-3} \text{ eV}$ is

$$\frac{y^2}{4\pi} \frac{1}{G m_p^2} \left(\frac{Z}{A} \right)_1 \left(\frac{Z}{A} \right)_2 < 1.3 \times 10^{-2} \quad (6)$$

which leads, introducing the conservative values for (Z/A) of 0.4,

$$y < 7.8 \times 10^{-20} \quad (7)$$

To obtain now a limit on M , we will simply put the value of the log in (3) equal to 1; this will lead to a conservative limit since $\Lambda \gg m_p$. With this, we obtain

$$M > 4.2 \times 10^{16} \text{ GeV} \quad (8)$$

Such a high lower bound implies that no signal of a 0^+ particle of mass $m_\phi \sim \text{meV}$ should be seen in experiments like PVLAS [7] or CAST [6]. In order to reach our conclusion we have to assume that the lagrangian (1) is valid up to high energy scales $\Lambda \gg m_p$.

We can proceed in analogous way and find bounds for other values of m_ϕ^{-1} . They are shown in Fig. 2, and as we see, the limits on M are very tight.

Our final discussion is about modified $\phi\gamma\gamma$ vertices. Examples of such models have been developed in [18] with the motivation of making compatible the PVLAS particle interpretation with the bounds coming from stellar energy loss and a fortiori with the CAST results. In these models the ALP does couple to new paraphotons and has not a direct coupling to photons. The $\phi\gamma\gamma$ vertex arises because there is kinetic photon-paraphoton mixing. Also, a paraphoton mass μ induces an effective photon form factor such that the coupling is reduced for $|q| \gg \mu$.

When there is a form factor with a low scale μ , the analysis shown in this paper should be modified accordingly. In such a case the lagrangian in (1) is valid only for photons with momentum q such that $|q| \ll \mu$. The induced Yukawa will be suppressed with respect to the value (3), and thus the lower bound (8) can be very much relaxed if indeed μ is a low energy scale.

In order to quantify our last assertion, we have calculated the induced Yukawa coupling when the photons have a modified propagator

$$\frac{1}{q^2} \rightarrow \frac{1}{q^2} \frac{\mu^2}{\mu^2 - q^2} \quad (9)$$

Now the diagram of Fig.1 is finite. The calculation of the coupling to protons y' , at leading order in μ/m_p gives

$$y' = \frac{\alpha}{4} \frac{\mu}{M} \quad (10)$$

To find the potential between bodies we have to take into account the coupling to protons as well as to electrons, because (10) is independent of the mass of the fermion. The potential when having a form factor (9) is given by

$$V(r) \simeq G \frac{m_1 m_2}{r} \left[1 + \frac{4}{G m_p^2} \frac{y'^2}{4\pi} \left(\frac{Z}{A} \right)_1 \left(\frac{Z}{A} \right)_2 e^{-m_\phi r} \right] \quad (11)$$

We see that the new non-standard potential (11) has a Yukawa coupling y' that compared to (3) is suppressed by a factor of order μ/m_p . The parameter μ introduced in [18] is not fully specified by the theory. In order to solve the PVLAS-CAST puzzle and if we do not wish too different scales in the model, μ should be in the subeV range with a preferred value $\mu \sim \text{meV}$. For this value, the bound (8) would relax by 12 orders of magnitude, bringing it close to the PVLAS value $M \sim 10^5 \text{ GeV}$. Remarkably enough, experiments searching for new forces and testing Casimir forces at the submm lengths may be sensitive to the potential (11) that corresponds to a vertex with the form factor (9).

Note added : The fact that a scalar-photon-photon coupling gives rise to new forces and leads to a bound on M has been independently realized by Shmuel Nussinov [19].

Acknowledgments

EM and JR acknowledge support by the CI-CYT Project FPA2005-05904 and the DURSI Project

2005SGR00916. We thank Pierre Sikivie for pointing out to us that a form factor relaxes the bound on M , and Holger Gies and Seth Hoedl for useful discussions.

-
- [1] S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978); F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).
 - [2] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); Phys. Rev. D **16**, 1791 (1977).
 - [3] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983) [Erratum-ibid. **52**, 695 (1984)].
 - [4] L. Maiani, R. Petronzio and E. Zavattini, Phys. Lett. B **175**, 359 (1986).
 - [5] S. J. Asztalos *et al.*, Phys. Rev. D **69**, 011101 (2004) [arXiv:astro-ph/0310042].
 - [6] K. Zioutas *et al.* [CAST Collaboration], Phys. Rev. Lett. **94**, 121301 (2005) [arXiv:hep-ex/0411033].
 - [7] E. Zavattini *et al.* [PVLAS Collaboration], Phys. Rev. Lett. **96**, 110406 (2006) [arXiv:hep-ex/0507107]; see talks of G. Cantatore and G. Ruoso at IDM 06, http://elea.inp.demokritos.gr/idm2006_files/talks/
 - [8] G. Carugno *et al.*, Phys. Rev. D **55**, 6591 (1997).
 - [9] C.D. Hoyle *et al.*, Phys. Rev. D **70**, 042004 (2004).
 - [10] D. J. Kapner, T. S. Cook, E. G. Adelberger, J. H. Gundlach, B. R. Heckel, C. D. Hoyle and H. E. Swanson, [arXiv:hep-ph/06011184]; E. G. Adelberger, B. R. Heckel, S. Hoedl, C. D. Hoyle and D. J. Kapner, [arXiv:hep-ph/0611223].
 - [11] J. O. Dickey *et al.*, science **265**, 482 (1994); J. G. Williams *et al.*, Phys. Rev. D **53**, 6730 (1996).
 - [12] R. Onofrio, New Journal of Physics **8** (2006) 237.
 - [13] Y. Su *et al.*, Phys. Rev. D **50**, 3614 (1994).
 - [14] J. K. Hoskins, R. D. Newman, R. Spero, and J. Schultz, Phys. Rev. D **32**, 3084 (1985); R. Spero, J. K. Hoskins, R. D. Newman, J. Pellam, and J. Schultz, Phys. Rev. Lett. **44**, 1645 (1980).
 - [15] S. J. S. Smullin, A. A. Geraci, D. M. Weld, J. Chiaverini, S. Holmes, and A. Kapitulnik, Phys. Rev. D **72**, 122001 (2005), [arXiv:hep-ph/0508204].
 - [16] J. Chiaverini, S. J. S. Smullin, A. A. Geraci, D. M. Weld, and A. Kapitulnik, Phys. Rev. Lett. **90**, 15101 (2003), [arXiv:hep-ph/0209325].
 - [17] S. K. Lamoreaux, Phys. Rev. Lett. **78**, 5 (1997); S. K. Lamoreaux, Phys. Rev. Lett. **81**, 5475 (1998).
 - [18] E. Masso and J. Redondo, JCAP **0509**, 015 (2005) [arXiv:hep-ph/0504202]; Phys. Rev. Lett. **97**, 151802 (2006) [arXiv:hep-ph/0606163].
 - [19] S. Nussinov, private communication.